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Insight, part of a Special Feature on Archetype Analysis in Sustainability Research

Archetypical opportunities for water governance adaptation to climate change

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ABSTRACT. We explore opportunities for climate adaptation in the context of water governance. We focus on opportunities linked to the provision of climate information, raising the question of whether they are limited to incremental adaptation, or can also bring about transformational adaptation. We address this question through an archetype analysis based on 26 peer-reviewed articles. In each article, opportunities are identified, coded using the social-ecological system framework, and then bundled into archetypes that encompass similar opportunities reappearing across multiple cases. Results suggest that the provision of climate information can constitute an opportunity for adaptation that goes beyond purely incremental adjustments to a changing climate. Specifically, two of the six archetypes identified enable transformational adaptation by bringing long-term implications of current impacts into focus and by addressing the issue of capacity of existing institutions to respond to climate change. However, there is a high degree of heterogeneity in the characterization of opportunities, and the six archetypes only cover about one in three of the opportunities identified. This indicates the need for further research to develop more streamlined conceptualizations. In this respect, the archetypes identified herewith suggest some avenues for further conceptual development. We also explore policy implications, raising questions regarding the current development of climate services.

Key Words: *adaptation; archetypes; climate change; climate information; opportunities; transformation; water governance; water management*

INTRODUCTION

A certain degree of climatic change is unavoidable, even if greenhouse gas emissions were to completely stop as of today (IPCC 2014). This makes adaptation to climate change necessary. Adapting social-ecological systems to a changing climate requires adjustments in both individual and societal behavior (Smit and Wandel 2006). Changes will be needed, both to implement technical solutions and to adjust to those climate impacts that technical solutions cannot fully offset (Adger et al. 2009).

Research into the societal dimension of adaptation focuses on two main lines of inquiry: barriers to adaptation (Moser and Ekstrom 2010) and maladaptation (Juhola et al. 2016). The former addresses the challenges practitioners and decision makers face in responding to increasingly adverse effects of climate variability and change (Biesbroek et al. 2013, Oberlack and Eisenack 2014, Lehmann et al. 2015, Moser et al. 2019). The latter points out that not all adaptation is good (Eriksen et al. 2011); some adaptation processes lead to maladaptive outcomes (Juhola et al. 2016), while others raise fairness and justice concerns (Paavola and Adger 2006, Pelling et al. 2015). In a nutshell, adaptation is difficult to roll out, and may go wrong. Therefore, careful consideration is required before taking measures to overcome barriers to adaptation.

Recent developments call for renewed reflection on these issues. One frequently cited barrier to adaptation is the inadequate provision of climate information to support decision making (Archie et al. 2014, Donatti et al. 2017). However, this barrier is now being overcome as sustained technical and institutional advances in climate modeling (Street 2016, Brasseur and Gallardo 2016, Simpkins 2017) make climate information increasingly accessible to decision makers. In the European context, for instance, a roadmap for climate services (Street 2016) sets out the first steps toward a future where administrations, businesses, and private citizens can easily access climate information. Despite the growing provision of climate information, there often remain challenges in integrating it into decision making and the ambiguity of what sort of adaptation will then follow.

We contribute toward this problem by linking two emerging discourses in the adaptation literature: on opportunities and transformation. The former discourse reflects a growing interest in going beyond a negative discussion of barriers, toward a positive understanding of factors that are currently enabling and shaping adaptation (Biesbroek et al. 2014, Oberlack 2017). The latter acknowledges the increasing importance of distinguishing between incremental and transformational adaptation (Kates et al. 2012, Lonsdale et al. 2015). These considerations enable us to formulate the following research question: Does the provision of climate information provide opportunities for both incremental and transformational adaptation? Or does it lock adaptation governance into either option?

Intuitively, climate information might appear to provide inputs primarily for incremental adaptation, i.e., the consideration of future climatic conditions in present-day decision-making processes. Transformation, by contrast, entails more fundamental alterations in existing governance structures (Pelling and Manuel-Navarrete 2011, Godfrey-Wood and Naess 2016), raising issues that go beyond mere availability of information. However, climate information also has a role to play in transformational adaptation. In fact, recent studies suggest that the generation, exchange, and contextualization of climate information is at the very heart of the transformational adaptation agenda (e.g., Tabara et al. 2018). Whether access to climate information provides opportunities for transformational adaptation as well as incremental change is thus a nontrivial question that merits a closer look.

In this paper we explore the links between provision of information and opportunities for incremental and/or

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transformational adaptation in the context of water governance. The water sector is severely affected by climate change (IPCC 2013, Tilleard and Ford 2016) and decision makers in the sector were quick to realize that governance solutions were required, as well as purely technical ones (Gupta and Pahl-Wostl 2013, Huitema et al. 2016). The sector is also characterized by a high degree of heterogeneity and fragmentation (Edelenbos and Teismann 2013, Eisenack 2016). These traits are typical for adaptation in general (Morrison 2017, Den Uyl and Russel 2018), and for transformational adaptation in particular (Lonsdale et al. 2015, Patterson et al. 2017).

Taking account of this heterogeneity, we address the research question using archetype analysis, a methodological approach increasingly gaining traction in sustainability science that enables researchers to develop scientifically valid generalizations about heterogeneous phenomena (Eisenack et al. 2006, Eisenack 2012). In this study, we apply archetype analysis to identify recurring patterns in situations where opportunities for adaptation are observed in the water sector. Subsequently we assess the extent to which these opportunities favor incremental or transformational adaptation. Based on 26 selected case studies on water governance adaptation from around the world, we identify six archetypical situations in which the provision of climate information constitutes an opportunity for adaptation. We find that four archetypes bear the hallmarks of incremental adaptation, while two are associated with transformational adaptation.

KEY CONCEPTS

Does the provision of climate information constitute an opportunity for both incremental and transformational adaptation in the context of water governance? We draw on a literature review to examine key concepts that underpin our formulation of this research question, i.e., water governance; climate information; adaptation governance; opportunities for adaptation; and incremental and transformational adaptation.

Water governance

Although water management has traditionally been the remit of central public authorities, contemporary water management is better described by the broader notion of water governance. This term encompasses the interactions among a variety of public and private organizations dealing with water resources at different levels of politico-administrative organization (Brooks 2002, Huntjens et al. 2010, Bressers and Kuks 2013, Pahl-Wostl and Knieper 2014). Water governance is a complex action field, involving different sectors, scales, and domains; it encompasses a complex structure of mutual interdependencies among actors with various interests and views that need to be coordinated (Edelenbos and Teismann 2013, Eisenack 2016).

In this context, the attention of academics and practitioners has shifted away from purely technical approaches to managing water and is now increasingly focused on achieving effective interaction and coordination among all actors involved (Edelenbos and Teisman 2013). This shift is reflected in the range of measures put forward to reduce the sector's vulnerability to climate change: although "hard" technical measures, e.g., raising dikes, have not gone out of fashion, they are increasingly embedded into "soft" approaches, involving spatial planning instruments and promotion of ecosystem-based perspectives ("living with water," "giving space to the river," "good ecological status"). These typically require that higher level water managers cooperate with local authorities (Kirchhoff et al. 2013) and water engineers engage with nature conservation agencies, planners, and affected parties (Bergsma 2016). Although an in-depth exploration of water governance is beyond the scope of this paper, the reader should keep in mind that the water sector has grown in social complexity, making interactions among interdependent actors crucial for the management of water resources.

Climate information and adaptation governance

As in the case of water governance, climate adaptation in general involves a broad set of actors, who play out in nested governance systems (Bisaro and Hinkel 2016). Adaptation governance corresponds to "collective efforts of multiple societal actors to address problems, or to reap the benefits, associated with impacts of climate change" (Huitema et al. 2016), with the aim of ensuring coordinated action among interdependent actors (Roggero 2015). Collective action faces social dilemmas, and climate adaptation is no exception in this respect (Bisaro and Hinkel 2016). Under the header of barriers to adaptation, scholars have identified many factors that prevent adaptation from taking place (Moser and Ekstrom 2010, Biesbroek 2014, Lehmann et al. 2015, Oberlack 2017). Many of these barriers relate to the provision of climate information.

Climate information refers to externally provided processed data, products, or evidence-based knowledge about the atmosphere-ocean system (Singh et al. 2018). This climate data originates from diverse sources such as in situ sensor measurements, remote sensing observations, or climate models (Giuliani et al. 2017) and can range from historical data to long-term climate change projections (Soares et al. 2018). Such diversification leads to a wide range of available climate information that can be used in adaptation decision making, different in its origin, form, purpose, scale, or context. The temporal character of such information is particularly important for climate adaptation. Climate information can be divided into three categories: short term (weather forecasts); medium term (seasonal and decadal climate forecasts), and long term (climate variability and climate change projections; Collins 2002, O'Brien and Vogel 2003, Ziervogel et al. 2010). There are important differences between these types of forecasts: weather forecasts predict conditions of the atmosphere, i.e., temperature, precipitation, and air movements, for the next few days, while climate forecasts are based on the statistical average of all weather events over a longer period of time (normally 30 years; Singh et al. 2018).

In the water sector, climate change projections and medium-term climate predictions play the greatest role in preparing strategic, longer term adaptive responses (Ziervogel et al. 2010, Kirchhoff 2013). However, generation of future climate information through modeling or scenario-based approaches (usually using general or regional circulation models and emission scenarios) is often associated with users' concern regarding accuracy of such information (Grygoruk and Rannow 2017) or uncertainty about projected climate impacts (Biesbroek et al. 2014). Scholars have identified a number of further challenges related to the integration of climate information into planning and decision making. These include unwieldy rules that hamper the retrieval, processing, and use of information for decision making (Oberlack and Eisenack

2018), institutional fragmentation (Cosens et al. 2017, Okpara et al. 2018), lack of collaboration (Bettini et al. 2015) and communication (Azhoni et al. 2017), and inadequate awareness and understanding of climate change (Jones and Boyd 2011, DeCaro et al. 2017).

Opportunities for adaptation

Within the adaptation literature, two fundamentally different concepts share the label of "opportunity" for adaptation: drivers forcing adaptation (see Shepherd et al. 2006, Pelling and Manuel-Navarrete 2011), and factors enabling adaptation (see Lonsdale et al. 2017, Oberlack 2017). The distinction is subtle, but important. For example, an adaptation measure that results from the traumatic experience of a flood is different from one that results from the reorganization of public administration. Both cases represent an opportunity for adaptation. Yet, they represent qualitatively different phenomena: in the former, an unforeseen catastrophic event leads to new perceptions and priorities. In the latter, an organizational measure is taken intentionally to remove a specific barrier to adaptation (see Tompkins et al. 2010).

Both concepts are important and relevant. However, because of space considerations, we focus in this study on opportunities as enabling factors, and specifically on opportunities related to the provision of climate information that help overcome existing barriers to adaptation in the water sector. The rationale for this choice is that opportunities that force adaptation can only be seized upon in a reactive way, however timely this may be. By contrast, removing barriers intentionally requires careful consideration, particularly if doing so can potentially give rise to different types of adaptation. Opportunity in this sense is thus more closely aligned to the topic of our research.

Incremental and transformational adaptation

The distinction between incremental and transformational adaptation emerged as a topic of interest when climate scholars started to highlight the need for a fundamental change in socioeconomic arrangements in order to adapt to climate change (Tabara et al. 2018), and to question whether the measures currently planned and/or being taken are up to the task (Kates et al. 2012). The defining characteristics of transformational adaptation have been described in different ways: as addressing the root causes of climate vulnerability rather than only its symptoms (Wise et al. 2014); fostering long-term adaptive capacity rather than short-term vulnerability reductions (Wamsler et al. 2013); or changing habits and institutions rather than the physical infrastructure (Vine 2018). All in all, scholars seem to converge around an emphasis on long-term, reflexive adaptation processes.

Precisely drawing the line separating incremental and transformational adaptation has so far proved challenging. In principle, the distinction is similar to one that has been widely discussed in the literature of evolutionary resilience. It is recognized that a resilient social-ecological system can display two different reactions in response to an external shock: it can absorb the shock and "bounce back" to status-quo conditions or, alternatively, "bounce forth" to a new set of conditions that are equally stable and yet fundamentally different (Davoudi et al. 2013). In this sense, incremental adaptation encompasses measures that reproduce or even entrench the status quo in the face of changing conditions. By contrast, transformational adaptation encompasses measures that lead to a new system configuration.

METHODS

We aim at identifying recurring patterns in situations where opportunities for adaptation are observed in the water sector. Below we provide an overview of the methodology used to generate research insights that are more widely applicable than single-case idiosyncrasies, but also of more practical relevance than overgeneralized panaceas.

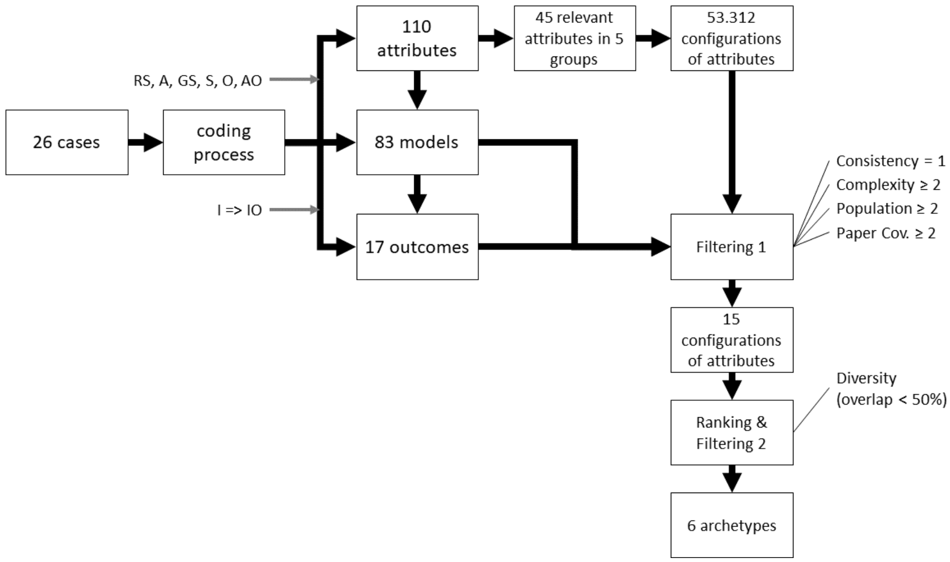
Research design and data collection

We conducted a meta-analysis of 26 systematically selected research articles to identify opportunities to adaptation, using the social-ecological system (SES) framework (Ostrom 2009) to characterize each opportunity identified. Specifically, we used the articles selected by Oberlack and Eisenack (2018) for their study of barriers to adaptation in worldwide water governance (see Appendix 1 for full references). In all these case studies, opportunities for adaptation were also identified, making this selection suitable for the present analysis.

Similar to Oberlack (2017) and Oberlack and Eisenack (2018), our meta-analysis is "model-centered" (Rudel 2008); that is, it focuses on explicit causal statements found in the articles under review, and draws collections of attributes ("models") from each of them. The rationale for this procedure is as follows. Conducting a meta-analysis of multiple case studies carried out by different authors with different goals in mind would ideally involve interviews and/or questionnaires with the authors to fill gaps and establish a degree of homogeneity in the dataset. Doing so is a resource-intensive process and goes beyond the available resources. As an alternative, the model-centered approach represents a viable second-best option. Because models are derived from explicit statements, they require less interpretation than the case study as a whole. Focusing on causal statements clearly represents a reduction of complexity. That should not be overstated, though, first, because causal statements were formulated by experts with case-level knowledge, and second, because they passed the peer-review process, which, with all its limitations, should guarantee a minimum degree of reliability. Third, causal statements should not be overstated because they can represent a substantially large and considerably detailed amount of text.

The last point is crucial. When the phenomenon at stake is well-studied, model-centered meta-analyses can take a very reductionistic approach to identifying causal statements and drawing models from them (e.g., Oberlack 2017, Oberlack and Eisenack 2018). "Opportunities for climate adaptation," however, is an emerging concept, with little research to rely on. Causal statements shall therefore provide a sufficiently rich description so as to cover the whole situation in which an opportunity for adaptation arises. To this end, we deviate from Oberlack (2017) and Oberlack and Eisenack (2018) and broaden our understanding of causal statements to include the broader account in which they are embedded. Causal statements shall therefore be read as explicit narratives, providing a rich description of how a particular enabling factor (provision of climate information), when coupled with other factors leads to adaptation to climate change. A detailed illustration of how

Fig. 1. Data analysis flowchart.



models were extracted from the source material can be found in Appendix 1.

We identified a total of 83 models in the 26 articles under scrutiny. Of these, 38 models describe an opportunity in terms of the provision of climate information. We coded these 38 models employing the common vocabulary of attributes developed by Oberlack and Eisenack (2018), which builds on the SES framework. The SES framework has a multitiered structure that allows opportunities identified to be coded at varying levels of specificity. Moreover, it is very comprehensive and is thus able to accommodate a broad set of very different situations. In a nutshell, the SES framework is both broad and deep and does not impose, ex ante, a specific level of abstraction on the analysis (see Cox 2008). This is useful when exploring potentially very heterogeneous phenomena such as opportunities for adaptation.

Our codebook retains the top-tier of the framework, distinguishing between resource systems (RS), resource units (RU), actor characteristics (A), governance systems (GS), social, economic, and political settings (S), and interactions (in our study labeled IO, so as to reflect opportunities), to which the additional category "adaptation option" (AO) was added. The second and third tiers of the codebook divide each of these categories into a further set of attributes, which were similarly modified by the authors to fit the data. One of the main authors undertook multiple rounds of coding, discussing results with the other authors to ensure inter-rater reliability of coding. Iterations continued until the codebook stabilized. In its final form the codebook comprises 116 attributes; of these, 6 describe the opportunity concerned (IO), and 110 characterizing the factors affecting it, distributed across several tiers of RS, A, GS, S, and AO. Appendix 1 contains detailed information on the final codebook and coding process.

Data analysis

We employed archetype analysis to explore the 38 models relevant to the provision of climate information, searching for patterns among their attributes. The reader can refer to Oberlack et al. (2019) and Eisenack et al. (2019) for a detailed account of the broader rationale underlying archetype analysis. In the context of the present research, there were two main reasons for our decision to employ archetype analysis. First, opportunities for adaptation can be expected to encapsulate a high level of heterogeneity, particularly in the context of water governance. We therefore needed an analytical approach that favors multiple, contextualized explanations, rather than single, universal ones. Second, we needed an approach that is compatible with multiple levels of abstraction, i.e., the multiple tiers of the SES framework that we employed to organize and structure the data. Archetype analysis fulfills both requirements.

Archetype analysis does not represent an analytical method per se. Rather, it is an approach compatible with multiple analytical methods (Sietz et al. 2019). It provides guidelines on how to structure an analysis in order to systematically search for possible attribute configurations (here the 110 attributes of the modified SES framework) in a given set of observations (here the 38 models of adaptation linked to the provision of climate information). Figure 1 shows how the guidelines for archetype analysis were translated into a procedure, leading from the characterization of the models to the identification of the archetypes. A full description procedure can be found in Appendix 1; here we summarize its most important features:

- From the original list of 110 attributes, we removed those that were observed in fewer than three models, leaving a total of 45. Subsequently, all theoretically possible configurations of these 45 attributes encompassing one attribute from each SES element (including no attribute) were computed.
- The resulting 53,312 theoretically possible configurations were then filtered based on four criteria: (1) whether they identify models that consistently feature opportunities for adaptation that involve the provision of climate information ("consistency"); (2) whether they were reoccurring, i.e.,

observed in at least two models ("population"), (3) from at least two different papers ("coverage"); and (4) whether they encompassed at least two different SES elements ("complexity").

- This process resulted in a list of 15 configurations that were then ranked based on their complexity (number of attributes) and population (the number of models). The resulting ranking was used to structure pairwise comparisons between configurations to remove those that overlapped beyond a fixed threshold (50%). This resulted in the final list of six archetypes, described below.

The analysis was done using R (R Core Team 2018). The derived archetypes satisfy the quality criteria for archetype analysis (Eisenack et al. 2019), namely: (1) they have a clear domain of validity (water governance); (2) they are not mutually exclusive (individual models can be instances of multiple archetypes, even though no two archetypes can cover exactly the same set of models); and (3) they are reoccurring (the corresponding models must appear in at least two different papers).

RESULTS

This section presents the six archetypes that were identified using the procedure outlined above, and completes the archetype analysis by describing the theories underpinning them.

Adaptation as collective action

This archetype reflects the combination of three attributes: "joint institutional arrangements," "trust building among actors," and "horizontal coordination"; it was observed in two different models from two different papers. Joint institutional arrangements, trust building among actors, and horizontal coordination are key descriptors of collective action, which has been a central theme in the literature on adaptation (Marshall 2013, Bisaro and Hinkel 2016). Scholars particularly stress the importance of interdependencies among actors and the crucial role of social dynamics in building adaptive capacity (Adger 2003). We observed this archetype in the context of transboundary water governance, where water management is typically fragmented. Coordination between the parties and the presence of common institutional frameworks are essential to enable adaptation. Establishment of joint institutions helps to reconcile multiple interests, balance priorities, and shape a favorable environment for the integration of climate information into decision making and design of feasible management interventions (Kistin and Ashton 2008).

Adaptation through local knowledge

The attributes making up this archetype are "local watershed units" and "awareness of climate change impacts," appearing in three models across three papers. This archetype highlights the link between the "local" dimension of the watershed concerned and impacts of climate change. It thus encompasses those branches of the adaptation literature addressing the (single) "level" of socioeconomic organization best suited to deliver adaptation and stressing that local actors know best how climate change translates into impacts (Brooks 2002, Agrawal 2008, Nordgren et al. 2016). At the local level, climate impacts might be grasped more easily, which gives climate concerns a higher chance to be integrated into management practices. Experience of local-level vulnerability to climate change motivates actors to integrate climate information into water management practices and deliver effective responses (O'Connor et al. 1999). Adaptation here takes place within existing practices.

Adaptation "fit"

This archetype describes the combination of "local watershed units" and "institutional incentives and priorities." It represents three models from two different papers. Like the previous one, this archetype reflects the scholarly debates on the most appropriate level of adaptation. Here, however, the focus is on the alignment of institutional incentives with the requirements for local-level adaptation in response to climate impacts experienced at this level. This relates to a broader debate in the literature on environmental governance regarding the correspondence between institutional boundaries and the costs and benefits linked to managing particular resources (Young 2002, Young 2010), a topic that adaptation scholars have also addressed (Farber 2009, Shobe and Burtraw 2012). From this perspective, the provision of climate information represents an opportunity for adaptation if it is provided in a way that fits with the interests and mandates of the (local) actors concerned (Whitely Binder 2006, Hamlet 2011, Hurlbert and Diaz 2013).

Knowledge in context

The attributes characterizing this archetype are "local watershed units" and "available data on climate projections at the local scale," identifying two models from two different papers. Climate research literature on scenario building highlights the need for highly contextualized knowledge for decision making (Cohen 1990, Hostetler 1994, Grimmond et al. 2010). It is often difficult for decision makers to know how to respond to low-resolution climate projections. In contrast, opportunities for adaptation emerge when climate information is provided at a local scale (O'Connor et al. 1999, Whitely Binder 2006). Speaking the language of local climate impacts makes climate information more accessible to decision makers, and more relevant to existing mindsets, institutions, and biophysical particularities (Füssel 2007).

System evolution

Combining "current climate stimuli" and "long-term focus," this archetype reflects two models from two papers. Literature at the intersection between resilience and climate adaptation highlights the need for adaptation to climate change to be informed by a vision of the long-term development of the social-ecological system concerned (Tschakert and Dietrich 2010, Davoudi et al. 2013). In this sense, opportunities for supporting long-term and effective adaptation arise from the coproduction of useful knowledge as a result of collaboration between scientists and stakeholders (Kirchhoff et al. 2013, Pulwarty and Maia 2015). Such direct collaboration between stakeholders and climate scientists aims at improving stakeholders' understanding of climatic stimuli and its impacts on the governed water system. It reconciles information supply and concrete demand needs by integrating expertise from both sides, which leads to increased capacity while dealing with adaptation related problems. This kind of partnership implies long-term iterative interactions that allows for advancing formal and informal networks, and therefore is likely to result in successful and sustainable societal outcomes. Specifically, such collaborations go beyond the mere planning of individual measures, directly impacting regional policies and promoting development of new communities of practices (as in Wilder et al. 2010).

Learning

This archetype combines "awareness of climate impacts" and "institutional incentives and priorities" as observed in two models from two papers. Much of the literature on adaptation focuses on learning, stressing how adaptation often needs to be compatible with shared beliefs about the workings of the social-ecological system (Pahl-Wostl 2009, Baird et al. 2014). Learning plays a crucial role in shaping actors' behavior, particularly when regulatory arrangements are unwieldy and complex, and/or insufficient on their own to foster the direct integration of climate change concerns in formal decision-making processes (Storbjörk 2010). The key insight is that learning ensures a higher level of awareness of climate impacts among managers and decision makers. It enables actors to circumvent institutional barriers to adaptation by exploiting flexibility in existing arrangements and seeking synergies with other institutional arrangements. For example, recognition of potential adverse effects of climate variability on a resource system and of the need for a tailored climate information may result in seizing opportunities by integrating climate change issues into decision making under the umbrella of related existing institutional mechanisms that prioritize efficient use and conservation of water resources (Boer 2010, Farley et al. 2011). This leads to a higher adaptive capacity in terms of increasing institutional flexibility and ensures long-term, reflexive adaptation.

DISCUSSION

Our archetype analysis identifies six recurring situations in which opportunities for adaptation in water governance arise. The analysis focuses specifically on opportunities linked to the provision of climate information and whether these opportunities are for incremental or transformational adaptation. Results suggest that the provision of climate information is not limited to adaptations consisting of incremental, marginal changes in existing practices, but are also associated with transformational adaptation. Specifically, two of the six archetypes identified, "System evolution" and "Learning," enable transformational adaptation, in the former as a result of the focus on long-term implications of current impacts, and in the latter arising from reflection among actors on how to address climate impacts in the context of available institutional arrangements. These two archetypes fit well into narratives characterizing transformational adaptation as adaptation that (1) focuses on reducing future vulnerabilities rather than simply preserving present conditions; and (2) questions the capacity of existing institutions to respond to climate change (Mustelin and Handmer 2013, Lonsdale et al. 2015).

In relation to the overarching research question addressed by this study, these results are encouraging: they suggest that the provision of climate information can constitute an opportunity for adaptation that goes beyond purely incremental adjustments to a changing climate. This result is particularly encouraging in the light of the current situation, where barriers to adaptation translate into a lack of tangible adaptation measures on the ground (Berrang-Ford et al. 2011). Although uncertainty, ambiguity, and lack of information are known barriers to adaptation, the opportunities that emerge to overcome such barriers are apparently not restricted to incremental adaptation. Removing barriers through the provision of climate information will not, it seems, lock adaptation governance into an incremental approach. At least under certain circumstances, it can also give rise to transformational change.

Given the exploratory nature of this study, it seems too early to draw conclusions from the actual composition of the archetypes identified here. Instead, it is probably safer to regard them as starting points for further research. From this perspective, with reference to the two "transformational" archetypes highlighted above, advancements in the conceptualization of opportunities for adaptation shall be linked to the way social-ecological systems evolve over time and to possibilities for double and triple-loop learning as a key step toward change. With reference to the other "incremental" archetypes, advancements seem to lie on collective action, as well as on matters of scale, given that three of the remaining four archetypes stress the local dimension of the resource unit. Future research will tell if developing concepts of opportunities for adaptation along these lines will align with empirical observation.

By focusing primarily on the analysis of opportunities for climate adaptation, the present study identifies archetypical situations in which integration of climate information constitutes an opportunity for adaptation and on the nature of adaptation that follows. Given the increasing amount of available climate information for adaptation decision making, it is worthwhile for future research to consider how different types of climate information are used in different ways and can thus influence opportunities for adaptation. There are already first attempts in this direction (Haasnoot et al. 2012, Singh et al. 2018, Hinkel et al. 2019). The archetype approach may also play a role here by informing the development of climate services, for instance by providing tailored climate products and information.

With a rapid development in provision of environmental information as well as in all kinds of information and communication technologies, processing and constantly governing growing amounts of data has become increasingly challenging. The case of information provision for climate adaptation is certainly no exception. Several questions emerge: what new data should be gathered? Who is responsible for collecting and processing the data, coordination of databases, and dissemination of information? How can this data and information be shared and combined to ensure more sustainable decision making and how the impact can be monitored? We are thus about to observe a great shift in the role information is playing within the governance context. A further link to the emerging field of research in informational governance and environmental sustainability is worth exploring as well (Soma et al. 2016, Giuliani et al. 2017).

Having outlined the implications of the present analysis for adaptation research, we can now tentatively explore the policy implications. The fact that the provision of climate information can enable transformational adaptation calls for policy support in boosting collaborative processes and social learning, e.g., building knowledge hubs (Ziervogel et al. 2016). Leaving aside the distinction between incremental and transformational adaptation, the overarching message emerging from the archetypes seems to be that opportunities for adaptation arise when the provision of climate information is embedded in a broader process. In this respect, current efforts by policy makers to establish new climate services and further develop existing ones are a welcome development, which may well contribute to boosting adaptation. These efforts are more likely to facilitate adaptation if policy makers adopt a process orientation (Brasseur and Gallardo 2016). However, judging from initiatives such as the European roadmap for climate services, at present there is a focus on developing markets for climate services (Street 2016), thus making them product oriented. It remains to be seen whether these efforts will be successful in promoting adaptation, or whether they will give rise to new barriers.

A limitation of this research is that the analysis focuses on research papers dealing with water governance, a field where both adaptation and transformation are well-established concepts. Although this is convenient for our analysis, it also limits the external validity of our results: opportunities for adaptation in other sectors such as developmental aid or agriculture may look very different. This is particularly the case for the two transformational archetypes whose specific features are closely linked to water management discourses such as adaptive management and social learning.

Furthermore, the fact of relying on a rather specific field such as water governance may prove a double-edged sword. On the one hand, it may facilitate the emergence of archetypes, given the similarity of perspectives within a narrowly defined epistemic community. On the other hand, it may also be a source of blind spots in the analysis: articles will not report about those things water governance scholars are not interested in. This is a general problem for meta-analyses. It may be less of an issue here, though, given the tendency of governance scholars toward rich case description.

A further limitation is that the analysis focuses on literature addressing barriers to adaptation, not opportunities. This was unavoidable, given the scant attention adaptation scholars have so far given to opportunities. The implications of relying on articles about barriers to adaptation are two-fold. First, scientific publications have limited space: given that opportunities were not the main focus of the papers, one cannot help wondering whether some opportunities, and if so how many, did not make it into the final manuscripts because of space limitations. Second, it becomes difficult to disentangle opportunities and barriers: opportunities identified by our research may, to some extent, simply be mirror images of the barriers the same articles report upon.

Some considerations are due concerning the low number of models covered by the six archetypes; specifically, opportunities linked to the provision of climate information were identified in 13 models out of 38. Given that the archetypes were constructed inductively and not deductively (that is, they were not formulated on the basis of prior knowledge), this is quite remarkable. Moreover, models were grouped on the basis of shared general characteristics, i.e., higher tier attributes of the SES framework, whenever they diverged with regard to details (lower tier attributes). This procedure resulted in archetypes characterized by rather general attributes, and yet even these covered only two or three models in each case. This suggests that opportunities for climate adaptation represent a very heterogeneous research field. A certain degree of convergence, and development of more streamlined conceptualizations, can be expected as the field reaches maturity. Time will tell whether future research using more sophisticated conceptual approaches enables the identification of suites of archetypes that provide a better coverage of the observed models.

Despite these limitations, this study confirms the ability of archetype analysis to identify and meaningfully interpret patterns of attributes in a very heterogeneous field. It is thus a promising approach for application in a field such as climate adaptation in the water governance sector where context dependence makes it extremely difficult to draw lessons that are valid beyond the individual case study. Archetype analysis has the potential to deliver research insights at an intermediate level of abstraction: more widely applicable than single-case idiosyncrasies, but also of more practical relevance than overgeneralized panaceas.

CONCLUSION

In this study we explored opportunities for climate adaptation in the context of water governance. We focused on opportunities arising from the provision of climate information. Further, we asked whether these are limited to opportunities for incremental adaptation, or whether provision of climate information can also give rise to transformational adaptation. To address this question, we carried out an archetype analysis of opportunities for adaptation described in 26 peer-reviewed research articles. In each article, opportunities were searched for, coded using the SES framework, and finally bundled into archetypes that encompass similar opportunities reappearing across multiple cases. Six such archetypes were identified, each one representing an opportunity for adaptation characterized by a distinct set of attributes. Two of these archetypes are associated with specific narratives in the discourse on transformational adaptation, suggesting that opportunities for adaptation linked to the provision of climate information are not necessarily limited to incremental adaptation. However, the results display a high degree of heterogeneity in the characterization of opportunities, indicating the need for further research to develop more streamlined conceptualizations of the phenomenon. The results of this study suggest some avenues toward further conceptual development that could be explored by future studies of opportunities for climate adaptation.

Responses to this article can be read online at:
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Data Availability:

Data sharing is not applicable to this article because no new data were created or analyzed in this study.

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Appendix 1

CASE SELECTION AND CODING

To reveal specific conditions that explain the appearance of opportunities for achieving climate adaptation, we conduct an archetype analysis of 26 selected case studies on water governance adaptation in river basins worldwide. The selection of these primary cases is based on the study of Oberlack and Eisenack (2018), where barriers to adaptation are thoroughly explored. This allows for examination of factors that enable adaptation opportunities in the context of already identified adaptation barriers. The studies were retrieved from the databases of Web of Science and Scopus so that the research is based on primary data and the articles are peer-reviewed. The final sample included primary studies on water governance adaptation in river basins worldwide from 20 scientific journals for the period of 1990-2015 (Table A1.1).

River basin	Reference
Watersheds in Washington State (USA)	Binder, L. C. W. 2006. Climate change and watershed planning in Washington state. *Journal of the American Water Resources Association* 42: 915–926
McKenzie River (USA)	Farley, K.A., C. Tague, and G.E. Grant. 2011. Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy. *Global Environmental Change* 21: 110–122
Yahara River (USA)	Gillon, S., E.G. Booth, and A.R. Rissman. 2015. Shifting drivers and static baselines in environmental governance: Challenges for improving and proving water quality outcomes. *Regional Environmental Change* 16: 759–775
Columbia River (USA)	Hamlet, A.F. 2011. Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Sciences* 15: 1427–1443
Susquehanna River (USA)	O'Connor, R.E., B. Yarnal, R. Neff, R. Bord, N. Wiefek, C. Reenock, R. Shudak, C.L. Jocoy, P. Pascals, and C.G. Knight. 1999. Weather and climate extremes, climate change, and planning: Views of Community Water System Managers in Pennsylvania's Susquehanna River Basin. *Journal of the American Water Resources Association* 35: 1411–1419
Bear river basin (USA)	Welsh, L.W., J. Endter-Wada, R. Downard, and K.M. Kettenring. 2013. Developing adaptive capacity to droughts: The rationality of locality. *Ecology and Society* 18: 7
Jaguaribe-Banabuiu Basin, Itajai Basin (Brazil) and Watersheds in Arizona and Georgia (USA)	Kirchhoff, C.J., M.C. Lemos, and N.L. Engle. 2013. What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the U.S. *Environmental Science & Policy* 26: 6–18
Colorado River (Mexico, USA)	Pulwarty, R.S., and T.S. Melis. 2001. Climate extremes and adaptive management on the Colorado River: Lessons from the

	1997–1998 ENSO event. *Journal of Environmental Management* 63: 307–324
Arizona-Sonora region (Mexico, USA)	Wilder, M., C.A. Scott, N.P. Pablos, R.G. Varady, G.M. Garfin, and J. McEvoy. 2010. Adapting across boundaries: climate change, social learning, and resilience in the U.S.–Mexico border region. *Annals of the Association of American Geographers* 100: 917–928
Colorado River (Mexico, USA) and Guadiana River (Portugal, Spain)	Pulwarty, R.S., and R. Maia. 2015. Adaptation Challenges in Complex Rivers Around the World: The Guadiana and the Colorado Basins. *Water Resources Management* 29: 273–293.
Southern Saskatchewan (Canada)	Hurlbert, M., H. Diaz, D.R. Corkal, and J. Warren. 2009. Climate change and water governance in Saskatchewan, Canada. *International Journal of Climate Change Strategies and Management* 1: 118–132
Okanagan (Canada)	Shepherd, P., J. Tansey, and H. Dowlatabadi. 2006. Context Matters: What Shapes Adaptation to Water Stress in the Okanagan? *Climatic Change* 78: 31–62
Columbia River (Canada, USA)	Cosens, B.A., and M.K. Williams. 2012. Resilience and Water Governance: Adaptive Governance in the Columbia River Basin. *Ecology and Society* 17: 3
Southern Saskatchewan (Canada) and Elqui (Chile)	Hurlbert, M.A., and H. Diaz. 2013. Water Governance in Chile and Canada: A Comparison of Adaptive Characteristics. *Ecology and Society* 18: 61-83
Mendoza (Argentina) and Oldman River (Canada)	Hurlbert, M.A., and E. Montana. 2015. Dimensions of Adaptive Water Governance and Drought in Argentina and Canada. *Journal of Sustainable Development* 8: 120-137
18 river basins in Brazil	Engle, N.L., and M.C. Lemos. 2010. Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change* 20: 4-13
Aconcagua River (Chile)	Hill-Clarvis; M. and Allan; A. (2014): Adaptive capacity in a Chilean context: A questionable model for Latin America. Environmental Science & Policy, 43, 78–90.
Aconcagua (Chile) and Rhone (CH)	Hill, M. 2013. Adaptive capacity of water governance: cases from the Alps and the Andes. *Mountain Research and Development* 33: 248–259
Guadiana River (Portugal, Spain)	Cots, F., J.D. Tàbara, D. McEvoy, S. Werners, and E. Roca. 2009. Cross-Border Organisations as an Adaptive Water Management Response to Climate Change: The Case of the Guadiana River Basin. *Environment and Planning C* 27: 876–893
Multiple rivers in Denmark	Larsen, S.V. 2011. Risk as a challenge in practice: Investigating climate change in water management. *Regional Environmental Change* 11: 111–122

Orange-Senqu River (Botswana, Lesotho, Namibia, South Africa)	Kistin, E.J., and P.J. Ashton. 2008. Adapting to Change in Transboundary Rivers: An Analysis of Treaty Flexibility on the Orange-Senqu River Basin. *International Journal of Water Resources Development* 24: 385–400
Catchments in northeast Queensland (Australia)	Boer, H. 2010. Policy options for, and constraints on, effective adaptation for rivers and wetlands in northeast Queensland. *Australasian Journal of Environmental Management* 17: 154–164
Murray-Darling Basin (Australia)	Pittock, J., and C.M. Finlayson. 2013. Climate change adaptation in the Murray-Darling Basin: Reducing resilience of wetlands with engineering. *Australian Journal of Water Resources* 12: 161-169
Murray-Darling Basin (Australia)	Wei, Y., J. Langford, I.R. Willett, S. Barlow, and C. Lyle. 2011. Is irrigated agriculture in the Murray Darling Basin well prepared to deal with reductions in water availability? *Global Environmental Change* 21: 906–916
Tweed River (Australia)	Singh-Peterson, L., S. Serrao-Neumann, F. Crick, and I. Sporne. 2013. Planning for climate change across borders: Insights from the Gold Coast (QLD) – Tweed (NSW) region. *Australian Planner* 50: 148–156
Elbe, Guadiana, Rhine, Nile, Orange, Amudarya	Krysanova, V., C. Dickens, J. Timmerman, C. Varela-Ortega, M. Schlüter, K. Roest, P. Huntjens, F. Jaspers, H. Buiteveld, E. Moreno, J. de Pedraza Carrera, R. Slámová, M. Martínková, L. Blanco, P. Esteve, K. Pringle, C. Pahl-Wostl, and P. Kabat. 2010. Cross-Comparison of Climate Change Adaptation Strategies Across Large River Basins in Europe, Africa and Asia. *Water Resources Management* 24: 4121–4160

Table A1.1 Primary case studies and river basins

Since selected case studies contain heterogenic data and contexts, we refer to archetype analysis. In such instance, this approach appears to be valuable in that it generates two extremes that one could run to by trying to identify some regularities: context-specificity and over-generalization. Archetypes are representative patterns of human-environmental interactions that are recurrently observed (Eisenack et al. 2006).

To identify interactions between various elements in adaptation situations coding methodology was used. Coding is a practical tool that is widely used for a qualitative analysis as it helps to systematically organize textual data. We coded text segments in the selected publications that describe situations, under which opportunities for adaptation emerge.

Development of codes for the present study on adaptation opportunities was based on the Ostrom's (2009) Social-Ecological Systems (SES) framework and on its modification for the climate adaptation context by Oberlack and Eisenack (2018). In most general terms, the SES framework encompasses outcomes (IO) in action situations framed by the core elements of the SES: resource systems (RS), resource units (RU), actors (A) and governance systems (GS) (Ostrom 2009). These elements or subsystems function within broader social-political-economic settings (S) and in the context of related ecological systems (ECO). The modification of the framework for the climate adaptation context involves the addition of the category “adaptation option” (AO) to characterize adaptation examined in a primary study. The elements introduced above represent first-tier categories in the SES framework. More detailed codes that include explanatory factors form second- and third-tier attributes of the adjusted SES framework (e.g. GS51 stakeholder participation, RS221 climate stimuli not (yet) experienced: flood).

Coding of the data from primary case studies was processed electronically with the use of the software MaxQDA. The segments of the case studies that proved to include explanatory factors form second- and third-tier attributes of the adjusted SES framework were systematically coded. This was done using at least one interaction attribute (IO) and at least another one from the remaining SES elements (RS, A, GS, S, or AO). Rationale for requiring at least one interaction attribute (IO) is that opportunities for adaptation were operationalized as an interaction attribute: whenever an interaction attribute is observed, an opportunity is observed as well. The interaction attribute represents thus the *outcome set* for the analysis of the data produced through the coding process.

If the interaction attribute represents the outcome set, the remaining attributes constitute the model inherent to each causal statement coded herewith. The model encapsulates the results of interactions documented in primary studies and is the unit of analysis. Therefore, similar to Oberlack (2017) and Oberlack and Eisenack (2018) our meta-analysis is “model-centered” (Rudel 2008). Rationale for focusing the analysis on models is the following: 1) models represent explicit statements, thus requiring less interpretation than the case as a whole; 2) although they represent a reduction of complexity, they were done by someone with case-level knowledge; and 3) they passed the peer-review process, which, with all its limitations, should guarantee a minimum degree of reliability.

The fact that our research aims at exploring opportunities for climate adaptation, which is yet an emerging concept and is less addressed in comparison to the concept of barriers to adaptation, requires a consideration of a wider unit of observation. This means that a pure causal statement where one factor or combination of factors lead to a particular outcome (see Oberlack 2017) does not allow to describe the whole situation, under which opportunities for achieving adaptation arise. This is why we discerningly deviate from the approach of pure „causal statements“ as in Oberlack (2017) and Oberlack and Eisenack (2018) and consider models as „narratives“ that describe how a particular enabling factor (e.g. provision of climate information) coupled with other factors (attributes from the SES framework) leads to adaptation to climate change. In this sense, models encapsulate the presence of adaptation due to provision of climate information (e.g. in contrast to adaptation due to institutional change) and other attributes that help to describe situations in which such adaptation emerge, which makes it possible to identify its nature (incremental vs transformational).

Some examples of how causal statements were identified and coded will help clarify how models came about. For a practical illustration we refer to the paper of Kirchhoff et al. (2013). The paper addresses the role of water governance regimes and boundary organizations in shaping climate information use. Kirchhoff et al. (2013) build their study on the analysis of data obtained from surveys of river basin councils’ members and interviews with water and disaster managers in the United States and Brazil. In search of causal statements, we look for text segments in the paper that explicitly link the characteristics of a particular situation to specific opportunities for adaptation. By doing so, we pay a particular attention that such explanations are found in direct presentation of the results and do not refer to some theoretical observations of other authors mentioned in the paper, i.e. they are not part of the literature review. Once such causality was observed, it was coded upon the common vocabulary of attributes.

One of the models we found in the study of Kirchhoff et al. (2013) crystallized out of the following text passage: "*In Arizona, interviews with water managers working with CLIMAS*[1] *revealed they were sensitive to climatic conditions and to other issues that affect water availability. These managers recognized that climate variability, and to a lesser extent climate change, may put water resources at increased risk in the future, given population growth and competition for water resources. Their perception of the vulnerability of water resources to climatic risks coupled with their goal of providing reliable water supplies was an important motivator for sustaining interaction with CLIMAS to produce usable climate information.*" We interpreted and coded this passage as following:

- Actor characteristics (A): this text segment allows for coding several actors' characteristics, such as "awareness of climate impacts", "understanding climate stimulus", "quality commitment", "availability of and accessibility to climate information". We assign these codes according to the sense that water managers' awareness of climate impacts and the recognition of the resource vulnerability to such impacts combined with a willingness to provide a reliable water supply sensitized water managers to information-seeking behavior.
- Resource system characteristics (RS): from the text passage, it becomes clear that the resource system is affected by a concurrent stimulus, a stimulus that is not related to climate issues, such as population growth in this case, but can likewise cause or exacerbate a water stress problem. We code it as a "concurrent stimuli".
- Adaptation option (AO): in order to understand how climate change may affect the water supply reliability in the future, water managers were seeking for relevant information to inform decision-making. This behavior of actors resulted in collaboration with the boundary organization aiming to generate usable information and thus to integrate climate impacts into planning and management settings. This is why we coded this as "adaptation responses due to interaction with boundary organizations".
- Governance system characteristics (GS): Such collaboration on information production requires an efficient interaction between actors and scientists from the boundary organization in order to reconcile information supply with a concrete demand, which we code as "coordination of data and knowledge" and "science-management interface".
- Opportunity for climate adaptation (IO): in the selected text segment, we can observe how the constellation of various factors (based on the SES framework) enable climate adaptation through production and use of climate information in planning and decision-making. Therefore, we consider sustained interaction with boundary organization as an opportunity for climate adaptation as it results in integration of climate impacts into governance and management practices, thus addressing a common barrier of water managers' risk aversion or skepticism.

For another example of model's extraction we refer to the study of Wilder et al. (2010) on adaptation of water resources in the U.S.–Mexico border region. The paper argues for a transboundary approach to increase regional adaptive capacity across borders. The study thus considers several cases of innovation in the regional strategies that aim at reconciling transboundary divide (Wilder et al. 2010). One of such innovations is the creation of a

[1] The Climate Assessment for the Southwest, a boundary organization in Arizona.

transboundary assessment program that specifically tends to fill the gap in the scientific knowledge on groundwater resources in the region, and as a result has a high potential for improvements in sharing of climate information and its better integration into planning and decision-making practices. The following text segment of the article was considered as a model: "*An emerging initiative, the U.S.–Mexico Transboundary Aquifer Assessment Program (TAAP), seeks to overcome these institutional and water-resource challenges through binational collaboration. Authorized by U.S. federal law and funded by annual budget appropriations, TAAP is implemented by the U.S. Geological Survey and the state water resources research institutes of Arizona, New Mexico, and Texas, with collaboration from Mexican federal, state, and local counterparts as well as IBWC[2] and CILA[2]. (...) Over TAAP's brief lifetime, mutually defined priorities for Arizona's and Sonora's common Santa Cruz and San Pedro aquifers have been identified as vehicles for water for growth, adaptation to climate change, local aquifer-recharge programs, and institutional assessment of groundwater management asymmetries.*". We interpreted this model as following:

- Actor characteristics (A): we code the willingness of actors to collaborate on information sharing, thus improving information flow and building a shared vision in the region, as "homogeneous interests". We also interpret such initiative as a way towards "understanding of interdependencies" in the social-ecological system of concern. The exchange and use of information to address inter alia climate change translated into the code of "availability and accessibility of climate information".
- Governance system characteristics (GS): from the governance perspective, such collaboration explicitly results into effective coordination between the two parties; this is why we correspondingly code it as "horizontal coordination".
- Adaptation option (AO): adaptation responses in this case are due to "creation of joint initiatives" in order to address climatic pressures.
- Opportunity for climate adaptation (IO): the creation of the information-sharing program represents an opportunity for achieving adaptation since it prompts collaboration among actors that leads to improving information flows. As a result, it has potential to develop a more systematic integration of new, relevant information into planning and management practices.

The coding procedure was repeated twice. If the codes were changed while coding a new study, the already coded studies were re-examined, and if necessary were subjected to the coding procedure a third time. In this way, through a stepwise coding, a detailed codebook was inductively developed and refined. In the final round, all models were checked for the congruence with the final codebook. This translated to a data set of 83 models, 110 attributes that hold for them, spanning across five different SES elements, and 6 different outcomes. The corresponding codebook is reported below (Table A1.2).

Code		Interpretation
O	Outcome	
O1	Opportunity to adaptation is reported	A case study reports and explains an opportunity to climate change adaptation.
IO	Interaction outcome	

[2] International Boundary and Water Commissions in the US and Mexico

IO1	Enhancing climate information use	Enhancing the usability of relevant information in planning and management practices, necessary for responding to longer-term changes (intra-annual variability, evaluation of data on extremes and mean values, climate projections).
IO2	Adjusting government regulations	Changes in government regulations or institutional design.
IO3	Integration	Integrating various aspects (social, economic, climate, political, etc.) as well as all actors involved at different levels to prepare responsive actions to climate change adaptation.
IO4	Learning	Various social learning processes that help to address climate adaptation needs.
IO5	Collaboration and coordination	Involvement of the interested and affected stakeholders and/or agencies (building networks or coalitions) for the joint cooperation (information, knowledge and resources) to increase adaptive capacity.
IO6	Capacity building	Provision of information, water accounting and necessary resources either from government or from other institutions in order to favor adaptation.
A	Actors	
A1	Individual knowledge	
A11	Understanding climate stimulus	Actors understand how climate change may affect the resource system.
A12	Understanding SES	Actors have a good understanding of the system they operate in.
A13	Understanding interdependencies in a SES	Actors have a good understanding of interdependent elements of the system they operate in.
A14	Awareness of climate change impacts	Actors are aware about climate impacts or they have a perception to be exposed to climate them.
A2	Homogenous beliefs, interests and priorities	
A21	Homogeneous beliefs	Actors have homogeneous beliefs about climate change and its impacts.
A22	Interest in climate change	Interest in climate change of individual actors who perceive the vulnerability of the resource system towards climate impacts.
A23	Trust building among actors	All actors are pursuing cooperative strategies and common interests.
A24	Political (public) acceptability	Adaptation related actions do not conflict with political values.
A25	Quality commitment	A goal to provide a reliable water supply.
A26	Homogeneous interests	Development of homogeneous beliefs among actors as well as building a common vision.
A3	Access to material resources	Actors possess resources necessary for the adaptation process.

A31	Available financing	Actors have access to funding means.
A32	Increasing technical capacity	Actors are able to increase technical capacity to prepare adaptive responses to climate impacts.
A4	Access to information resources	
A41	Use of modelling tools	The use of modelling tools for predictions and analysis of climate impacts.
A42	Available data on climate change projections at the local scale	There is available data on climate change projections at the local scale.
A43	Information on the system and on climate events	The use of information on the system actors are operating in and on local climate events in decision-making.
A44	Provision and use of new/additional information	The use of new, updated/additional information on climate and/or climate impacts in decision-making.
A45	Use of information on past events	The use of information on past climate extreme events.
A46	Communication of information	Dissemination of relevant climate information and demonstration of climate impacts to managers in order to increase awareness about climate change.
A5	Staff resources	
A51	High professional staff	Professional managers show familiarity with climate variability and change, helping to bring climate impacts into decision-making process.
RS	Resource system	
RS1	Size and scale of a resource system	
RS11	A resource system is embedded in a larger water system	The examined resource system is a part of a larger system, which is relevant for analysis.
RS12	Upstream-downstream effects	A particular positioning of actors of the resource system that has implications for decision-making.
RS2	Stimuli and exposure	
RS21	Current climate stimuli	Current climate stimuli that affect the resource system.
RS211	Drought	
RS212	Flood	
RS213	High variability	
RS214	Low variability	
RS215	Other	
RS22	Climate stimuli not (yet) experienced	Expected climate stimuli in view of climate change.
RS221	Flood	
RS222	Drought	
RS223	Other	

RS3	Current state of a resource system	
RS31	Degradation of a system	The examined resource system is in a degraded condition.
RS32	Water pollution	Pollution of water resources is a critical issue and has impact on its quality.
RS4	Concurrent stimuli	The resource system is affected by a concurrent stimulus, e.g. development processes, population growth, etc.
GS	Governance system	
GS1	Scale of institutions	Temporal boundaries of institutional operation.
GS11	Continuity in formal capacity	Continuity in formal capacity after the planning process has been completed.
GS12	Change in administration	Changes in administration due to staff rotation (e.g. as a result of the elections).
GS2	Adaptiveness of institutions	The extent to which institutions are able to be changed.
GS21	Flexibility of institutions	Flexibility in procedures for institutional change.
GS22	Complex management system	Management or governance system is considered complex due to many actors involved in managing process.
GS23	Institutional learning	Learning process as a result of information and knowledge flow across all levels of government.
GS3	Social connectivity	Characteristics of institutionalised procedures (i.e. chains of actions, events and outcomes) and networks (i.e. connections between multiple positions and actors) that connect actors within and across tiers of social organisation.
GS31	Vertical coordination	Coordination between actors of the analysed resource system and other governance levels.
GS32	Horizontal coordination	Coordination between different departments of the same-level public organizations.
GS321	Coordination of data and knowledge	Coordination between actors/ different departments of public organizations at the same-level of decision-making for data and knowledge exchange.
GS322	Common efforts and resources	Coordination between actors/ different departments of public organizations at the same-level of decision-making for joint efforts and resources.
GS33	Top-down decision-making	Decision-making process is based on a hierarchical, top-down manner.
GS34	Decentralized governance system	The governance system is characterized as decentralized.

GS4	Rights and responsibilities	
GS41	Institutional incentives and priorities	
GS411	Long-term focus	Operational rules prompt long-term planning.
GS 412	Efficiency and conservation are included/prioritized	Adaptive needs of ecosystems are prioritised.
GS413	Rules based on historical hydrology	Operational rules are based on historic hydrologic conditions.
GS414	Updates	Regular updates of planning documentation.
GS42	Responsibilities	Attributes of position and choice rules that regulate the positions of participants and their actions associated to these positions.
GS421	Clear not-fragmented responsibilities/decision-making	Responsibilities are clear.
GS422	Fragmented responsibilities	There are multiple independent actors of decision-making that are not coordinated.
GS43	Property rights	
GS431	Secure property rights	Security of property rights is high.
GS431a	Secure property rights with fixed allocations	Security of property rights is high and they provide their holders with the right to a fixed amount of a resource (e.g. prior appropriation rule).
GS5	Actors	
GS51	Stakeholder participation	Eligibility of stakeholders to participate in decision-making.
GS52	Leadership	There is a strong leader in a stakeholder group that can influence decision-making process.
GS6	Social learning	Institutional attributes that shape how information, knowledge, values and preferences are constructed, communicated and accepted among participants.
GS61	Effective science-policy/science-management interface	The science-policy/science-management interface is effective in terms of social learning.
GS62	Institutional learning	Effective institutional learning, incl. learning process as a result of information and knowledge flow across all levels of government.
GS63	Learning from other examples	Learning from other examples or areas takes place.
GS64	Context specific	Social learning is based on the understanding of interdependencies of actors in SES.
GS65	Learning is based on past experiences	Learning is based on past experiences with climate variability.
GS66	Education of stakeholders	Communication with and education of stakeholders (and public).

GS7	Control	Type of control over the system's management and over the aggregate outcomes of an adaptation situation.
GS71	Centralized coordinated	Distribution of power and authority is well-coordinated under a hierarchical governance mode.
GS72	Polycentric	Distribution of power and authority among various well-coordinated centres.
AO	Adaptation Option	
AO1	Reactive adaptation	Fast responses that include prompt decisions in order to reduce the damage caused by climate extremes.
AO2	Adaptation responses complementary with	Adaptation responses are complementary with various management and planning acts/programs.
AO21	Nature conservation and management acts	
AO22	State planning/management acts	
AO23	Water allocation management	
AO24	Water conservation program	
AO25	Water agreements	
AO26	Adaptive management program	
AO3	Formation of institutional bodies	Adaptation requires formation of various types of institutional bodies for its planning and implementation.
AO31	Local watershed units	
AO32	Joint institutional arrangements	
AO33	Basin-based councils	
AO34	Interface organisations	

Table A1.2 Codebook

DATA PROCESSING: ARCHETYPE ANALYSIS USING R

Step 1: Definition of the outcome set

Each model extracted from the literature through the coding process described so far is linked to an outcome. Similarly, to all other SES elements above, interactions/opportunities (IO) are coded in a nested form. As a result, outcomes vary both in qualitative terms (IO1 vs. IO2 vs. IO3) and in terms of specificity (IO1 vs. IO11 vs. IO111). Furthermore, models vary in terms of how often they are observed, implying that some opportunities appear in a large number of models, whereas other ones appear more seldom. Finally, the nested nature of the SES framework implies that instances of e.g. IO111 are a subset of the instances of IO11, which in turn are a subset of IO1 – as for all remaining entries in the codebook.

Because of the qualitative difference between the various outcomes, each individual instance (IO1, IO12, etc.) is worth an analysis on its own account. This corresponds to running the algorithm described herewith with a different outcome set. Space and the specificity of the research focus of the paper do not allow for an analysis of all instances of opportunities observed. Since the concept of archetype implies reappearing phenomena, suitable outcomes are those that are frequently observed. Figure A1.1 below shows how frequently each instance of opportunity/driver is observed.

Given the distribution shown in Figure A1.1, IO1 ("the provision of climate information") seems the most feasible option: being observed in almost every other model (38 out of 83), it is specific enough to be qualitatively meaningful, yet it is generic enough to be observed in a large pool of models.

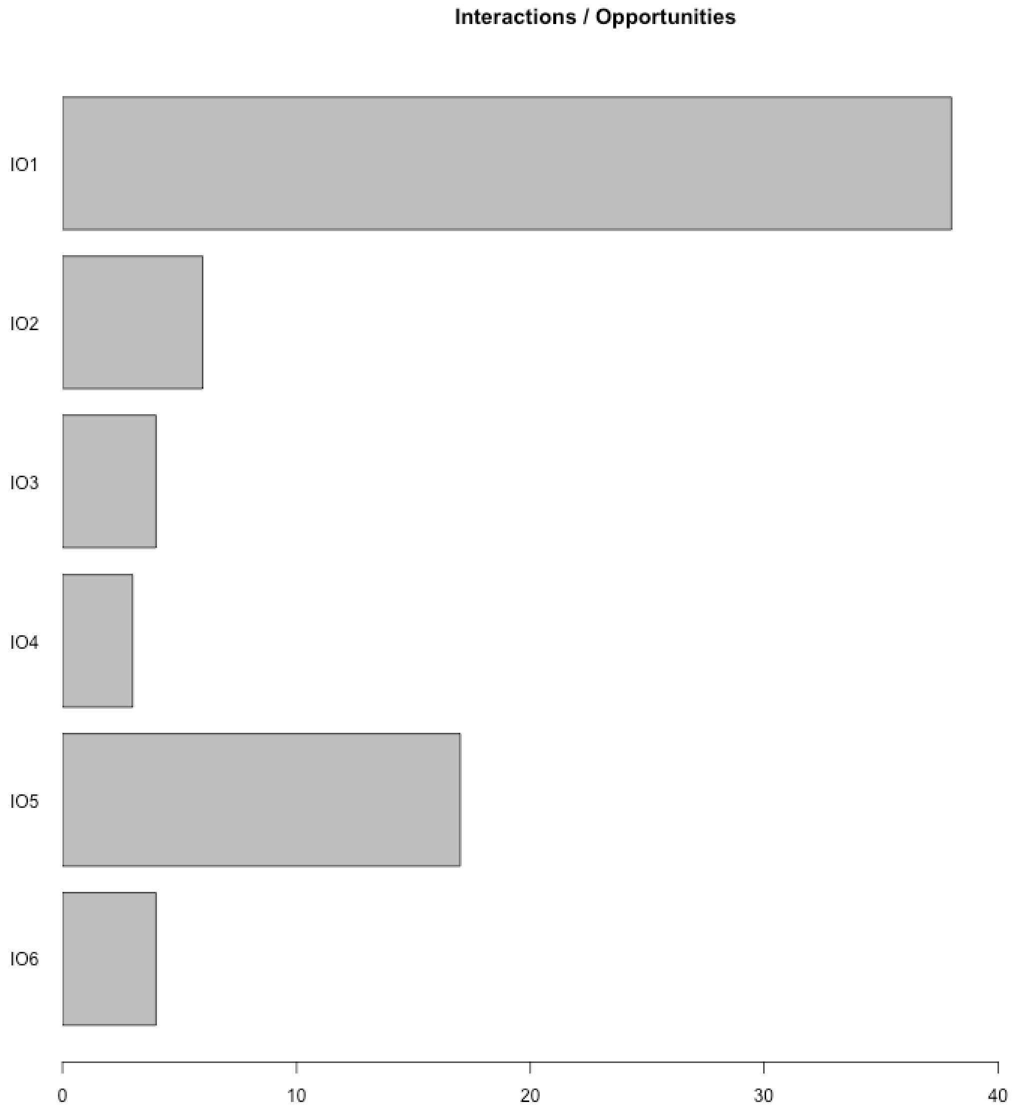

Figure A1.1: Number of models for each type of opportunity.

Step 2: identification of archetypes

To identify archetypical situations under which opportunities to adapt emerge, we processed the data on the models' attributes using R. We specifically wrote an algorithm that (ideally) computes all possible archetypes obtainable from the above mentioned 110 attributes, populates them with the available data, and tests whether the specific models identified by each archetype are consistently linked to the outcome set: IO1 or "enhancing the provision of climate information", the type of opportunity identified above.

Doing the above raises a few challenges. A key challenge is linked to computing all possible archetypes. The number of all possible combinations of 110 elements is the factorial of 110, which is in excess of 10^{178}. To express all theoretically possible archetypes alone is thus a computationally very intensive task – the more so if one also wants to verify which of the observed models is contained in each of them and link them to the outcome set. A more manageable task is instead to compute all possible archetypes that involve one (or no) attribute for each of those SES elements relevant for this study (RS, A, GS, S, and AO). Furthermore, attributes can be omitted if they are observed too seldom to appear in an archetype[3], or whether they are too general to be of interest. Eliminating such attributes further reduces the combinatorial space in which archetypes may potentially come about.

The above shortcuts produce a grand total of 53.312 computationally possible configurations of attributes. To obtain the corresponding models and test for the presence of IO1 programmatically is a feasible and rather straightforward task. That is however not a guarantee that the amount of relevant archetypes (those leading to IO1), will be in any way manageable. In order to achieve that, additional criteria are necessary. We have used a total of four, as detailed out below.

- The first of the four criteria corresponds to selecting those archetypes where IO1 is indeed *consistently observed*. Any given combination of SES elements (say: A131*GS21*AO3) yields a number of models which may or may not feature IO1 – for instance, some may feature IO2. In this first step, archetypes are retained if the models they yield *only* feature IO1. Please note that, while models featuring e.g. IO2 will lead the corresponding archetype to be discarded, models featuring more specific opportunities than IO1 (e.g. IO11 or IO123) will be retained. From an operational point of view, for each set of models identified by a particular archetype set-theoretic consistency as a sufficient condition for IO1 is calculated. Archetypes are retained if that consistency is 1.0, implying full consistency.

- Second and third, archetypes are required to feature in at least two models across at least two different papers. This two-fold requirement operationalizes the concept of archetypes as recurring patterns, taking into account that multiple models within the same archetypes may all come from the same publication and are thus only questionably "recurring". It is consistent with Oberlack and Eisenack (2018).

- Fourth, archetypes are selected based on their complexity, understood as the number of SES elements featuring therein. Specifically, archetypes are retained if they feature at least two different elements. We thus restrict the analysis to archetypes expressing the *combination* of *different* SES elements. Please note that this restriction has two

[3] By definition, an attribute observed only once cannot be observed in at least two models or papers. It thus cannot characterize an archetype, since archetypes need to be observed in at least two models from two different papers. More generally, the more seldom an attribute, the more unlikely it can appear in conjunction with other attributes. For the present analysis, the threshold has been set at three: attributes observed less than that were excluded from the analysis.

components: 1) that the *attributes* characterizing the archetypes must be more than one; and 2) that they must belong to different elements. As a result, archetypes made up of individual attributes are eliminated. Recall that archetypes are generated by computing all possible archetypes that involve one (*or no*) attribute for each SES element (RS, A, GS, S, or AO), which does not exclude archetypes encompassing a single attribute. Single-attribute archetypes, however, hardly fit the nature of archetypes as *patterns*. Leaving them out of the analysis is thus in order. Furthermore, archetypes encompassing more attributes from the same elements (e.g. GS12*GS15) *would* be eliminated as well. Such archetypes were not generated in the first place, though, as doing so would cause the number of potential archetypes to skyrocket. A mathematical proof is available here[4], but the reader can simply grasp this by comparing the amount of theoretically possible combinations of attributes (10^{178}) with the amount of archetypes obtained by combining one (or no) attribute for each individual SES element (53.312).

A first selection is then performed based on the four abovementioned criteria, leading to 15 relevant combinations of attributes. Although much more manageable, a similar selection of archetypes cannot ensure a meaningful diversity. The reader can easily grasp the issue by comparing a combination of attributes such as e.g. A13*GS21*AO31 with another one such as A131*GS21*AO3: both have the same degree of complexity, as they both involve three different SES elements; however, the former is more specific concerning adaptation outcomes (AO31 vs. AO3), whereas the latter is more specific concerning actor characteristics (A131 vs. A13).

What happens here is that any two combinations of attributes can be fundamentally similar, and increasing specificity on one hand can be off-set by decreasing specificity on another aspect of the archetype. These raises the question whether all archetypes characterized by a given selection of SES elements represent individually relevant archetypes, or whether they are better considered as variants of the same archetype, thus requiring further selection. The latter approach seems more meaningful in analytical terms, as it would ideally lead to results which are more parsimonious, and thus more amenable to theoretical interpretation.

In order ensure a degree of distinction between archetypes, these are first sorted lexicographically, based on complexity and, by equal complexity, by number of models. Based on that ranking, a last selection is performed, aiming at archetypes that, although different in terms of the attributes characterizing them, end up identifying the same set of models. Specifically, the selection process involves a pairwise comparison of archetypes, starting from the top ones and moving down the ranking. In each comparison, archetypes are eliminated if the models they encompass overlap beyond a certain threshold (50%). This means: if two archetypes overlap for more than 50 percent in terms of the models they identify, they are considered variants of the same archetype. In that case, the lower one in the ranking is eliminated. Note that, by proceeding in this way, individual models *can* be captured by different

[4] Assume $y = a + b$, where $a > 1$ and $b > 1$. It follows that $!y = (a + b) * (a + b - 1) * (\dots)$, so that $!y > (a + b) * (a + b - 1)$, meaning $!y > a^2 + b^2 + 2ab - a - b$. That can be expressed as $!y > ab + k$, where $k = a^2 + b^2 + ab - a - b$. It follows that $k > 0$ because $a^2 + b^2 + ab > a + b$. Hence, $!y > ab + k$, hence $!y > ab$, q.e.d.
Note that cases where either a or b are either nil or simply smaller than one are out of scope here, as they would respectively represent an entirely empty set ($a = b = 0$), a single-attribute archetype ($a = 0$ or $b = 0$) non-integer or even negative amounts ($a < 1$ or $b < 1$).

archetypes. What the procedure does not allow is that archetypes identify *sets of models* that overlap beyond a certain threshold.

When the comparisons are completed, the archetypes left in the ranking meet all the conditions needed in order to qualify as archetypes: they are linked to a certain "outcome" (IO1); they represent sets of attributes; they are observed in multiple cases (here: models from different articles); multiple archetypes can be observed in individual cases, yet different archetypes encompass sets of cases that differ from one another. Additionally, their complexity (how many attributes) is chosen systematically, as a result of the process described above.

Based on the dataset at stake, the number of archetypes identified with the procedure described so far amounts to the following 6:

Archetype	ATs	Number of models	Papers	Models
Adaptation as collective action	AO32, A23, GS32	2	2	Kistin and Ashton 2008 (02), Wilder et al. 2010 (01)
Adaptation through local knowledge	AO31, A14	3	3	Binder 2006 (09), Hurlbert and Diaz 2013 (04), O´Connor et al. 1999 (02)
Adaptation "fit"	AO31, GS41	3	2	Binder 2006 (07), Binder 2006 (08), Hamlet 2011 (03)
Knowledge in context	AO31, A42	2	2	Binder 2006 (13), O´Connor et al. 1999 (01)
System evolution	RS21, GS411	2	2	Kirchhoff et al. 2013 (03), Pulwarty and Maia 2015 (03)
Learning	AC14, GS41	2	2	Boer 2010 (03), Farley et al. 2011 (05)

Table A1.3 Archetypes of opportunities for enhancing climate information use.

The attributes encompassed thereby are the following:

ID	Code	Label
18	AO31	local watershed units
19	AO32	joint institutional arrangements
38	RS21	current climate stimuli
74	A14	awareness of climate impacts

78	A23	trust building among actors
88	A42	available data on climate projections at the local scale
105	GS32	horizontal coordination
112	GS41	institutional incentives and priorities
113	GS411	long-term focus

Table A1.4 Attributes of archetypes.